Observations and simulations of foreshock waves during magnetic clouds

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MAGNETIC CLOUDS DRIVE THE MOST INTENSE DISTURBANCES AT EARTH

Magnetic clouds = subset of coronal mass ejections

Properties in the interplanetary space [Burlaga et al., 1981]:
- Enhanced magnetic field
- Smooth rotation of the magnetic field direction

Because of their strong geoeffectivity, it is important to understand the details of their interaction with near-Earth space

Zurbuchen & Richardson (2006)
WHAT HAPPENS WHEN MAGNETIC CLOUDS CROSS THE EARTH’S FORESHOCK?

The foreshock is the sunward-most extent of geospace, populated by backstreaming particles, and hosting a variety of waves.

First region crossed by incoming solar wind and magnetic clouds.
WE FOCUS ON THE MOST COMMON FORESHOCK WAVES

- Foreshock mainly populated by waves with a period around 30 s [e.g., Eastwood et al., 2005]

- Fast magnetosonic waves generated through the ion-ion beam right-hand instability

30 s foreshock waves observed by the Cluster spacecraft
HOW CAN WE STUDY THE FORESHOCK PROPERTIES?

Numerical approach

Global kinetic simulations of near-Earth space performed with the Vlasiator code

→ global view of the foreshock
→ small-scale features

Observational approach

Observations from ESA’s four-spacecraft Cluster mission

→ accurate determination of the foreshock wave properties
Hybrid-Vlasov model designed for global magnetospheric simulations

- Ions treated as **velocity distribution functions**, electrons are a charge-neutralizing fluid
- Most runs are currently 5D – 3D in velocity space and 2D in ordinary space
- Full description of the model: Palmroth et al., 2018

Pl: Minna Palmroth (minna.palmroth@helsinki.fi)
VLASIATOR RUNS USED IN THIS WORK

• Run set-up:
  – Equatorial plane
  – Quasi-radial interplanetary magnetic field (IMF) (cone angle = 5°)
  – Solar wind parameters: \( V = 600 \text{ km/s} \); \( n = 3.3/\text{cc} \); \( T = 500 \text{ kK} \)

• **Run 1**: typical IMF strength (5 nT) \( \rightarrow M_A = 10 \) [Palmroth et al., 2015]

• **Run 2**: enhanced IMF strength (10 nT) \( \rightarrow M_A = 5 \) (“magnetic cloud-like” conditions)

→ Effects of the enhanced interplanetary magnetic field strength on foreshock properties
AN ENHANCED MAGNETIC FIELD MODIFIES THE LARGE-SCALE STRUCTURE OF THE FORESHOCK

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**Diagram Description**

**Panel a:** Ion density in Run 1
- Quiet solar wind conditions

**Panel b:** Ion density in Run 2
- Magnetic cloud-like conditions

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*Turc et al., 2018, JGR*
AN ENHANCED MAGNETIC FIELD CHANGES THE FORESHOCK WAVE PROPERTIES

During magnetic clouds, we find:

- A shorter foreshock wave period
  Consistent with previous works [Takahashi et al., 1984; Le & Russell, 1996]
- A more complex wave activity

Turc et al., 2018, JGR
FORESHOCK OBSERVATIONS DURING MAGNETIC CLOUD EVENTS ARE SCARCE

- Magnetic clouds are observed about 2% of the time at Earth [Yermolaev et al., 2012]
- Cluster is only sporadically located in the foreshock
- Spacecraft separations similar to the waves characteristic size mostly in the early phase of the mission
- 6 magnetic cloud events with left-handed foreshock waves
- 4 magnetic cloud events with confirmed 30 s waves
Foreshock wave activity becomes more intricate during magnetic clouds.

Quiet solar wind conditions

Magnetic cloud

Turc et al., 2019, GRL
MULTI-SPACECRAFT ANALYSIS CONFIRMS THAT THE WAVES ARE FAST MAGNETOSONIC

Determination of the wave properties

• **Multi-point signal resonator technique** [Narita et al., 2011] (variant of k-filtering/wave telescope method [Pinçon & Lefeuvre, 1991; Motschmann et al., 1996]) → ideal for cases with several wave modes

• **Timing analysis** [e.g., Eastwood et al., 2005] applied on bandpass-filtered data (to separate the co-existing periods) → easier to apply to a large number of intervals

→ superposition of fast magnetosonic waves at different periods
FORESHOCK WAVE ACTIVITY BECOMES MORE INTRICATE DURING MAGNETIC CLOUDS

Turc et al., 2019, GRL

Quiet solar wind conditions

Magnetic cloud

Timing analysis analysis and k-filtering → superposition of fast magnetosonic waves at different periods
THE WAVE FRONTS ARE MUCH SMALLER DURING MAGNETIC CLOUDS

Transverse extent (from multi-spacecraft analysis technique [Archer et al., 2005])

- Quiet solar wind conditions: 3-11 \( R_E \) (average: 7 \( R_E \))
- Magnetic cloud-like conditions: 2-6 \( R_E \) (average: 4 \( R_E \))
THE WAVE FRONTS ARE MUCH SMALLER DURING MAGNETIC CLOUDS

Cluster observations in the foreshock during 4 magnetic clouds

35 2-min intervals with fast magnetosonic waves during which we determine reliably the transverse extent of the wave fronts

→ 1-10 \( R_E \) (average = 3.5 \( R_E \)) < 8-18 \( R_E \) [Archer et al. 2005]
Magnetic clouds modify significantly the foreshock wave field

Both Vlasiator simulations and multi-spacecraft observations consistently show that during magnetic clouds, the foreshock is characterised by:

- a lower wave period
- the coexistence of fast magnetosonic waves at different periods
- smaller wave fronts

This could strongly affect the regions downstream:

- bow shock properties
- waves in the magnetosphere
- ...

CONCLUSIONS
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Visit https://www.helsinki.fi/en/researchgroups/vlasiator